

Composition and formation of the terrestrial planets

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URL	http://hdl.handle.net/10097/00131745

論文内容要旨

(NO. 1)

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学位論文の 題 目	Composition and formation of the terrestrial planets (地球型惑星の化学組成と形成過程)		

Comparative studies of terrestrial planets have provided important insights into physicochemical processes that produced their similarities and differences. Chemical composition of terrestrial planets records planetary accretion, differentiation, impact, and surface processes. In order to place new constraints on the origin and evolution of rocky planets, I investigated chemical compositions of terrestrial planets and meteorites from primitive asteroids (chondrites).

Compositional models of planets have found or assumed chondritic relative abundances of refractory lithophile elements (RLE). I challenge this fundamental paradigm by showing highly variable RLE ratios in individual chondrules from enstatite chondrites (EC), which are highly reduced primitive meteorites with Earth-like isotopic signatures. The fractionated RLE compositions of EC chondrules reflect moderately chalcophile behaviors of these elements and sulfide-silicate separation in highly reduced nebular environments. If the Earth's building blocks were dominated by highly reduced EC-like materials, they should not have been affected by a physical sorting of silicates and sulfides before their accretion. Alternatively, the Earth's precursors might have been high-temperature nebular materials that condensed before precipitation of the RLE-bearing sulfides. The bulk Mercury might not have chondritic RLE ratios, due to sulfide-silicate separation processes that formed its large metallic core.

Previous compositional models of Mars relied on an assumption of CI-chondritic relative abundance of Mn and more refractory elements, which has been challenged by recent astrophysical observations. Here I propose a new martian model composition that avoids such an assumption, using data from martian meteorites and spacecraft observations. The new model finds that Mars is enriched in refractory elements and show a systematic depletion of moderately volatiles as a function of their volatilities compared to the CI abundance. The Mars' volatile depletion trend indicates a S-poor composition for the martian core, which requires an incorporation of additional light elements (e.g., O, H) into the core to match the martian geodetic properties.

Earth and Mars are equally enriched in refractory elements, although Earth is more volatile-depleted and less oxidized than Mars. These compositional properties were established by a nebular fractionation, with negligible post-accretionary losses of moderately volatile elements. The degree of planetary and asteroidal volatile element depletion might correlate with the abundances of chondrules in the accreted materials, planetary size, and their accretion timescale. During its prolonged formation, the Earth likely accreted more chondrules and less matrix-like materials than Mars and chondritic asteroids.

The correlations between these planetary properties constrain the composition and origin of

Mercury, Venus, the Moon-forming giant impactor, and the proto-Earth. These observations, combined with the shared refractory enrichment in Earth and Mars, and insights from planetary uncompressed densities, establishes the compositional model of Mercury. Uncompressed densities of rocky bodies in the solar system decrease with their heliocentric distance, indicating a role of disk-scale metal-silicate separation before the planetary accretion, rather than post-accretionary modification processes.

Insights presented here update our knowledge of the origin of rocky planets in our solar system, and provide future perspectives on studies of chemistry of (extra)solar system bodies.

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論文審査の結果の要旨

本論文では地球型惑星の全球化学組成に直目し、太陽系平均組成からの元素分別の程度から、惑星の材料物質と形成プロセスをモデル化する研究を行った。特に火星の全球化学組成と内部構造を推定し、その化学組成から火星の材料物質がコンドリュールと呼ばれる原始惑星系円盤内部で形成された揮発性物質に乏しい高温形成物質が主成分であったこと、また、揮発性物質に富む細粒マトリックス物質は、惑星には選択的に集積しなかった可能性を指摘した。

過去に地球のマントル組成推定に適用された手法を適用し、最新の隕石や探査機により得られた火星の局所組成データを基に、火星のマントル化学組成を推定した。さらに熱力学的・測地学的数値モデルを組み合わせることで、火星の全球および金属核の化学組成も推定した。1. 火星は中揮発性元素の減少率が地球ほど大きくはないこと、2. 金属核には軽元素として硫黄に加え酸素や水素が含まれる可能性があること、3. 金属核は先行研究で提案されているサイズよりもかなり小さいこと、などが提案された。現在得られる最新の知見と原理を用い、火星全球の化学組成や内部構造をこれまでよりもより精密、かつ正確に評価したことが新しい。

火星や地球の全球化学組成が、惑星形成以前に原始惑星系円盤内部の高温過程で形成された1 mm大のコンドリュールに類似していることから、地球型惑星の主な材料物質はコンドリュールであることを提案した。一般的にコンドリュールは中揮発性元素が減少しており、地球や火星の組成をうまく説明できる。一方、現在の太陽系に存在する小惑星に残されたコンドリュールの化学組成は、地球や火星よりも中揮発性元素に富んでおり、これらのコンドリュールからは地球や火星を作ることができない。しかしながら、コンドリュールは太陽系誕生時から複数回形成されており、円盤内部で何度も加熱されることで経時的に中揮発性元素が増加されることが指摘されている。本論文では、地球や火星を作ったコンドリュールは初期に作られた中揮発性元素が乏しいコンドリュールであったことを指摘した。つまり地球や火星を作った材料物質は現在の太陽系には残されていないということである。これらのモデルは先行研究のモデルに比べ大きく進化しており、このことは吉崎氏が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、吉崎氏提出の博士論文は、博士（理学）の学位論文として合格と認める。